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CASE STUDY • RENEWABLE RESOURCES • WOOD

Environmental performance assessment of hardboard manufacture

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Abstract
Background, aim and scope The forest-based and related industries comprise one of the most important industry sectors in the European Union, representing some 10% of the EU's manufacturing industries. Their activities are based on renewable raw material resources and efficient recycling. The forest-based industries can be broken down into the following sectors: forestry, woodworking, pulp and paper manufacturing, paper and board converting and printing and furniture. The woodworking sector includes many sub-sectors; one of the most important is that of wood panels accounting for 9% of total industry production. Wood panels are used as intermediate products in a wide variety of applications in the furniture and building industries. There are different kinds of panels: particleboard, fibreboard, veneer, plywood and blockboard. The main goal of this study was to assess the environmental impacts during the life cycle of wet-process fibreboard (hardboard) manufacturing to identify the processes with the largest environmental impacts.
Methods The study covers the life cycle of hardboard production from a cradle-to-gate perspective. A hardboard plant was analysed in detail, dividing the process chain into three subsystems: wood preparation, board forming and board finishing. Ancillary activities such as chemicals, wood chips, thermal energy and electricity production and transport were included within the system boundaries. Inventory data came from interviews and surveys (on-site measurements). When necessary, the data were complemented with bibliographic resources. The life cycle assessment procedure followed the ISO14040 series. The life cycle inventory (LCI) and impact assessment database for this study were constructed using SimaPro Version 7.0 software.
Results Abiotic depletion (AD), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), ecotoxicity, photochemical oxidant formation (PO), acidification (AC) and eutrophication (EP) were the impact categories analysed in this study. The wood preparation subsystem contributed more than 50% to all impact categories, followed by board forming and board finishing, which is mainly due to chemicals consumption in the wood preparation subsystem. In addition, thermal energy requirements (for all subsystems) were fulfilled by on-site wood waste burning and, accordingly, biomass energy converters were considered. Several processes were identified as hot spots in this study: phenol-formaldehyde resin production (with large contribution to HT, fresh water aquatic ecotoxicity and PO), electricity production (main contributor to marine aquatic ecotoxicity), wood chips production (AD and OLD) and finally, biomass burning for heat production (identified as the largest contributor to AC and EP due to NO_X emissions). In addition, uncontrolled formaldehyde emissions from manufacturing processes at the plant such as fibre drying should be controlled due to relevant contributions to terrestrial ecotoxicity and PO. A sensitivity analysis of electricity profile generation (strong geographic dependence) was carried out and several European profiles were analysed.

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Discussion Novel binding agents for the wood panel industry as a substitute for the currently used formaldehyde-based binders have been extensively investigated. Reductions of toxic emissions during drying, mat forming and binder production are desirable. The improved method would considerably reduce the contributions to all impact categories.

Conclusions The results obtained in this work allow forecasting the importance of the wood preparation subsystem for the environmental burdens associated with hardboard manufacture. Special attention was paid to the inventory analysis stage for each subsystem. It is possible to improve the environmental performance of the hardboard manufacturing process if some alternatives are implemented regarding the use of chemicals, electricity profile and emission sources in the production processes located inside the plant.

Recommendations and perspectives This study provides useful information for forest-based industries related to panel manufacture with the aim of increasing their sustainability. Our research continues to assess the use phase and final disposal of panels to complete the life cycle assessment. Future work will focus on analysing the environmental aspects associated with plywood, another type of commonly used wood panel.

Keywords Fibreboard · Hardboard · Life cycle assessment (LCA) · Life cycle inventory (LCI) · Wet-process fibreboard · Wood boards · Wood panels

1 Background, aim and scope

Forest-based and related industries make up one of the most important and dynamic industrial sectors in the European Union (EU), representing some 10% of the total EU manufacturing industries. The EU forest-based industry constitutes one of the largest industrial sectors in Europe, providing direct employment and income to almost three million people. The European forest-based industry provides mainly for local and national needs and the companies are mostly small- and medium-sized enterprises (often family-owned); some of them employ less than 20 people and are not included in EU statistics. This has led to an underestimation of the socio-economic importance of the sector in the EU. Forest-based industries can be classified into the following five sectors: woodworking industry (from sawmilling operations to wood panel manufacture), pulp and paper industry, paper and board converting industry, graphic industry and furniture industry. Wood processing involves the conversion of trees into useful consumer products and/or building materials such as wood boards. The woodworking industries supply basic products such as sawn goods, wood panels and builders' carpentry for construction, internal decoration and packaging (pallets; European Commission 2008).

The overall consumption of panels in Europe reached record levels in 2006 (roughly 64.7 million m^3), driven by demand from end-use sectors: residential construction, furniture, cabinets, flooring and mouldings. The main breakdown of panels is particleboard, fibreboard, plywood and veneer sheet. The European panel industry, confronted with wood supply problems due to increasing competition with the biomass energy sector, is responding through a Renewable Energy Sources Working Group that provided their input to the EU Biomass Action Plan in 2005 (UNECE/FAO 2006).

Wood panels are characterised by their different physical and mechanical properties, which is a result of the structure and process engineering of these materials. The main panel types in Europe are particleboard, dry-process fibreboard (high-density (HDF) and medium-density fibreboard (MDF)) and wet-process fibreboard (hardboard), accounting for roughly 65% (particleboard) and 22% (fibreboard) of total panel production (excluding veneer sheets; UNECE/FAO 2004). Fibreboard is an engineered product made from compressed wood or non-wood lignocellulosic fibres. Because of their high resistance and strength, fibreboards can be used as a raw material for laminate flooring, exterior siding and trim, garage doors, high-quality furniture, wall panelling, interior trim and perforated boards. Nowadays, the consumer market is conscious of the environmental problems caused by product manufacturing and services. These environmental effects may negatively impact ecosystem quality and future availability of natural resources. Life cycle assessment (LCA) methodology has proved to be a valuable tool for evidencing and analysing the environmental impacts of products and service systems and should be part of the decision-making process toward sustainability (Baumann and Tillman 2004). Several studies have recently been carried out in relation to forest operations (Berg 1997; Berg and Lindholm 2005; González-García et al. 2009a, b), roundwood delivery (González-García et al. 2009c), wood floor coverings (Nebel et al. 2006; Petersen and Solberg 2003), particleboards (Rivela et al. 2006), MDF (Rivela et al. 2007) and related items such as window frames (Asif et al. 2002; Richter and Gugerli 1996), walls (Werner 2001) and furniture (Taylor and van Langenberg 2003). Wood products suitably installed and used tend to have a more favourable environmental profile compared to equivalent products from other materials (Werner and Richter, 2007). So far, no LCA studies are available for hardboard. The objective of this paper is to analyse the industrial process of hardboard manufacturing from an LCA perspective (UNECE 2006) to complete our previous works on the area of wood panels (Rivela et al. 2006, 2007).

2 Goal and scope definition

2.1 Objectives

This work aimed to analyse the manufacture of hardboard from an LCA perspective and to detect the environmental 'hot spots' throughout the production life cycle to improve the environmental performance. An Austrian hardboard plant with an annual production volume of 83,000 m^3 (2007) and considered representative of the state-of-art was selected to study the process in detail. The study covers the whole life cycle of hardboard production from raw material production to plant gate (a 'cradle-to-gate' system).

2.2 Functional unit

The functional unit provides a reference point for inputs and outputs (ISO 14040, 2006). In this paper, it is defined as 1 m^3 of finished hardboard (for interior applications) for a better comparison with other wood panels (Rivela et al. 2006, 2007). The board density is approximately 987 kg/m^3 and its moisture content ~7%.

2.3 Description of the system under study

The Composite Panel Association defines hardboard as a composite panel product consisting of lignocellulosic fibres (optionally combined with synthetic resin or other suitable bonding system) and joined together under heat and pressure (Composite Panel Association 2004). Additives such as paraffin wax can be used to improve certain characteristics such as abrasion and moisture resistance. A panel of this kind has uniform thickness, density and appearance and no grain. Hardboard is produced with the so-called wet process. The hardboard plant studied uses a smooth-one-side type production process, which affords good natural fibre to fibre interfelting and bonding with minimum added binder required and provides a moist surface of high plasticity giving the desired embossing sensitivity. This plant produces different hardboard grades with and without binder resin. Nowadays, hardboards are decreasing in importance compared to HDF due to the long press times required and their sensitivity to calliper increases. However, hardboards require lower amounts of resin than HDF, which is important from an economic and environmental perspective. The manufacturing process of hardboard involves (1) pre-heating of the raw material (e.g., softwood or hardwood chips) to soften the lignin and enable subsequent fibre separation, (2) defibration at high temperature and pressure, (3) resination, (4) forming the fibres into mats by using water as the distributing medium and (5) pressing the mats into boards in a hot press. The boards can be produced without synthetic resin but some grades are made with a small amount of phenol-formaldehyde resin. The main features of hardboard vary according to the brand but standard quality boards have a nominal width of 1,220–1,524 m and a moisture content of 2–9%. The board thickness is typically 2.0–9.5 mm, water absorption 15–40 wt. %, thickness swell 10–35 wt. %, modulus of rupture 31.0 MPa and tensile strength >0.60 MPa parallel to surface and >40 MPa perpendicular to surface. The board density ranges from 800 to 1,100 kg/m^3 (Ayrilmis 2007; Composite Panel Association 2004; Rowell Roger 2005).

The process chain was divided into three main subsystems: wood preparation, board forming and board finishing. Auxiliary subsystems such as chemical, thermal energy and electricity production, transport activities as well as wood chips production were also taken into account and computed. The system investigated is illustrated in Fig. 1.

Subsystem of wood preparation The main raw material is green wood chips from mostly Norway spruce (*Picea abies*) and European beech (*Fagus sylvatica*) delivered by truck from Austrian wood-based industries such as sawmills, satellite chip mills, etc. Initially, wood chips are washed to remove dirt and other debris. Clean chips and additional raw material from the plant (sanding dust, sawdust, trimmings, rejected hardboard etc.) are reduced into fibres and resinated (optional) as described above and placed in a storage bin. Part of the wood material is burned in biomass boilers to produce thermal energy for the plant activities.

Subsystem of board forming Fibres (with or without resin) are transported from the storage bin to the forming machine where they are deposited onto a moving conveyor and formed into a mat. The mat is pre-pressed and trimmed before being loaded into the hot press. This press applies heat and pressure to cure the resin (optional) and bond the fibres into solid boards during 4 min. Usually, the press uses a multi-opening batch press and is heated (to ~200°C) by steam produced at the thermal energy plant.

Subsystem of board finishing After pressing, the boards are first placed in a conditioning room and then fabricated by sanding and sawing into final size. Finally, the boards are packaged and sent to the warehouse for delivery to consumers. Trimming residues are recycled back to board production or used for on-site energy production.

Ancillary activities Several auxiliary activities were included within the system boundaries. Phenolic resin, paraffin emulsion and other chemicals production were part of the subsystem of wood preparation. In addition, their transport by truck from wholesaler to plant gate (roughly 300 km) was included in the study.

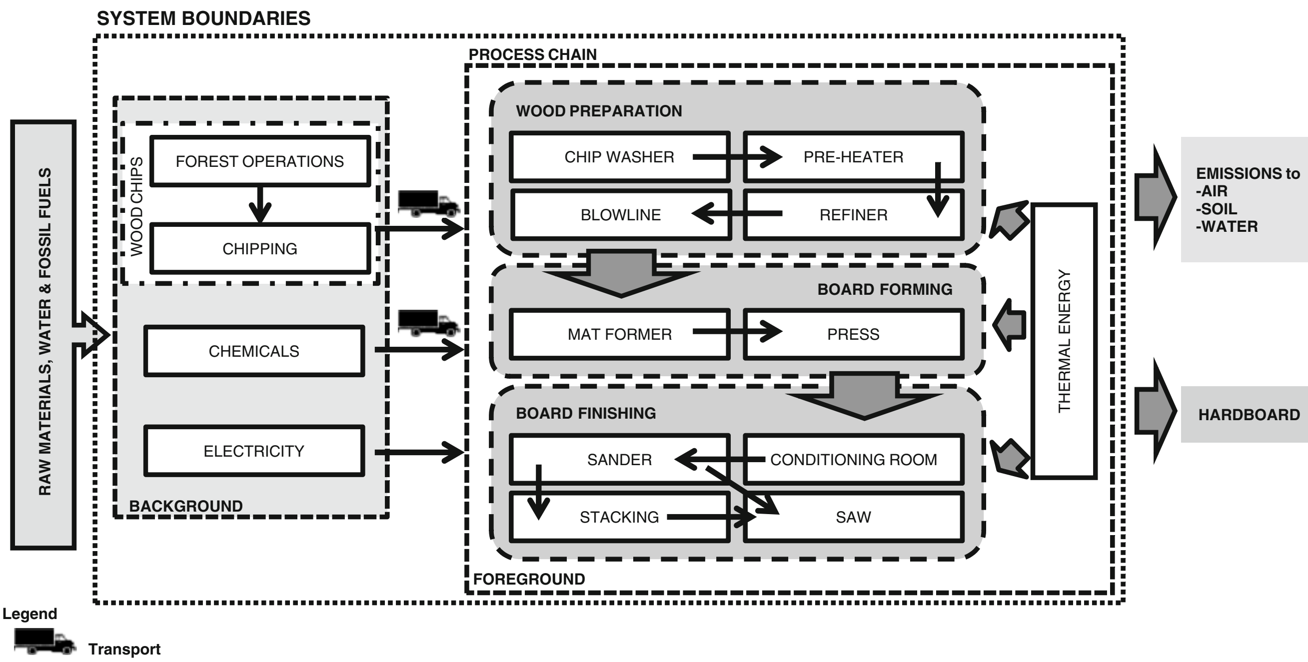


Fig. 1 System boundaries and process chain under study

Softwood chips production (main raw material) was included in the system boundaries considering from softwood plantation to roundwood chipping and delivery to fibreboard plant (Fig. 1). Although not specifically present in the figure, silviculture and logging operations as well as transport of roundwood to sawmill (100 km by truck) was taken into account in this study. It was assumed that all wood produced in that plantations is dedicated to chips manufacture because this kind of wood can be considered as raw material for other forest-based industries such as pulp mills. Moreover, transports of workers, machinery and materials (fertilisers, pesticides and fuels) to and from forest plantations were also included. Seedling production was excluded due to the lack of data. A more detailed description of these activities can be found in González-García et al. (2009a). Following, roundwood is processed into green chips, which will be delivered to the plant by truck (a distance of approximately 100 km).

The Austrian electricity generation profile was taken into account (79.7% from hydroelectric plants, 20.2% from fossil fuels (mainly hard coal and lignite) and 0.1% from renewable resources). Finished hardboard delivery was not included within the system boundaries due to the high geographic variability (local, regional, national and international distribution).

Finally, all the thermal energy consumed in the hardboard manufacturing process (steam, hot oil and hot gas) comes from biomass and is produced at the plant as described above. Wood waste from wood-based mills is used as fuel and its transport to plant gate (roughly 100 km) was included within the system boundaries.

2.4 Data quality and simplifications

Inventory data for the foreground system (hardboard manufacturing process) consisted of average annual data obtained by on-site measurements. Whenever possible and feasible, typical process-specific data were collected to avoid anomalous conditions.

The primary emission sources were dryers, presses, mat formers, the biomass boilers and finishing operations such as sanding and sawing. All emission data were field data except for the formaldehyde emissions corresponding to the wood preparation and board forming subsystems, which were estimated according to the emission factors reported by the US EPA for the year 2002 (US EPA 2002).

Other inventory data for the background system were obtained from databases, which are detailed below. Inventory data for resin, paraffin and aluminium sulphate production were taken from the Ecoinvent database (Althaus et al. 2007). Regarding Austrian electricity production, the assignment of the environmental loads was also obtained from the Ecoinvent database (Dones et al. 2007). Concerning forest operations related to softwood production, inventory data were taken from González-García et al. (2009a) where softwood plantations considered representative of the state-of-art were taken into account. Moreover, inventory data for the wood chipping stage were taken from ETH-ESU 96 (2004). Chemicals,

green chips and wood waste transportation routes were supplied by plant workers while emission factors were obtained from the literature (Spielmann et al. 2007).

When setting LCA boundaries, it must be decided whether the production of capital goods as well as their maintenance or replacement processes shall be included. In this study, the infrastructure production of the hardboard manufacture facilities was not included within the system boundaries since it was assumed to be comparable to that of plants producing functionally similar materials, any differences being negligible (Jungmeier et al. 2002a). The maintenance of capital goods (buildings, machinery, etc.) was also excluded from the study. Moreover, several industrial LCA studies have shown that the environmental load from the production of capital goods is insignificant when compared to their operation stage (Rivela et al. 2006, 2007). For this reason, the exclusion of such processes can also be justifiable. The inventory table of the global process is shown in Table 1 and extra data sources are summarised in Table 2.

2.5 Allocation procedure

A feature of the wood-based industry is the simultaneous production of diverse products. For the panel industry, the main product is the panel while residual wood is obtained as a by-product. An allocation procedure is only necessary for the panels since the residual wood is used for on-site generation of thermal energy. Forest waste was taken into account to complete the plant biomass energy balance. It was assumed no environmental burden allocation to forest waste from previous processes and only their transport and later processing were computed.

3 Environmental impact assessment

In the forest sector, LCA may allow proposing improvements for specific areas in the forest-wood chain and demonstrating environmentally satisfactory application of wood for industry and consumer markets (Karjalainen et al. 2001; Werner and Nebel 2007).

Of all the steps defined by the impact assessment stage in the LCA methodology (ISO 14040, 2006), only the classification and characterisation stages were considered. Normalisation and evaluation were excluded from the study since they are optional elements and would not provide additional useful information for the present study.

A retrospective LCA for hardboard manufacture was carried out according to the CML 2 baseline 2000 V2.1 biogenic method (Guinée et al. 2001) to quantify the environmental impact. This method results in the definition of an environmental profile for the assessed product/process/service by quantifying the environmental effects on different categories, while only indirect or intermediate effects on humans can be assessed. The impact categories analysed in this study were: abiotic depletion (AD), global warming (GW), ozone layer depletion (OLD), photochemical oxidants formation (PO), acidification (AC) and eutrophication (EP). In addition, toxicological impact

Table 1 Global inventory for 1 m^3 of finished hardboard

Inputs from technosphere			
Materials (kg)		Energy (MJ)	
Biomass		Electricity from grid	1,715
Green chips (50% moisture)	2,655	Thermal energy from biomass[a]	5,024
Forest waste	8.32	Transport (t·km)	
Chemicals		16 t truck	17.9
Phenol-formaldehyde resin	34.0	40 t truck	266.3
Paraffin emulsion	17.0		
Aluminium sulphate	8.5		
Outputs			
To technosphere		To environment	
Materials (kg)		Emissions to air (kg)	
Board finished (7% moisture)	987	CO biogenic[b]	0.60
		CO_2 biogenic[b]	470
		NMVOC[b]	0.26
		NO_x[b]	3.60
		SO_2[b]	0.55
		Dust and particulates[c]	0.090
		Filterable matter[c]	0.10
		Formaldehyde[c]	0.149

[a] Hot oil to press, hot gas to dryer and steam to defibrator

[b] Emissions corresponding to biomass boilers

[c] Emissions corresponding to dryer, mat former and press

Table 2 Summary of data sources

Energy	Electricity	Ecoinvent database (Dones et al. 2007)
Transport	Truck 16 t and 40 t	Ecoinvent database (Spielmann et al. 2007)
Chemicals	Resin, paraffin and aluminium sulphate	Ecoinvent database (Althaus et al. 2007)
Raw materials	Wood chips	ETH-ESU 96 database (ETH-ESU 96, 2004); González-García et al. (2009a)
Emissions	Formaldehyde	US EPA 2002 (US EPA 2002)

categories (human toxicity (HT), fresh water aquatic ecotoxicity (FE), marine aquatic ecotoxicity (ME) and terrestrial ecotoxicity (TE)) were also analysed although the LCA community has not yet reached a consensus on the characterisation models for their definition (Larsen et al. 2004). The LCA software SimaPro 7.10 developed by PRé Consultants (PRé, 2008) was used for impact assessment. The results for the characterisation step are shown in Table 3.

Figure 2 shows the relative contributions of the hardboard manufacturing process to each impact category investigated. It is seen that the wood preparation subsystem presented the highest contribution (>50%) to all categories, followed by board forming and board finishing. This result was due to its higher electricity use compared to the remaining subsystems and to the fact that only chemical consumption takes place in wood preparation. Furthermore, a more detailed study of each impact category was carried out; Fig. 3 shows the relative contribution of the main processes to each impact category. It is important to remark here that the process "wood chips" includes not only logs chipping stage but also forest production step.

Abiotic depletion potential This impact category is related to extraction of minerals and fossil fuels due to inputs in the system under study; it is expressed as kilogram of antimony-equivalent/kilogram of extraction. The wood preparation subsystem is the main contributor to AD (~100%), which is mainly due to diesel requirement for wood chipping stage (1.4 kg diesel per cubic meter of wood processed). Regarding the main substances contributing to this impact category, fossil fuels such as crude oil represented roughly 98% of the total contribution.

Table 3 Impact assessment results (characterization step) of hardboard manufacture for 1 m^3 of finished hardboard

Impact category	Unit	Value
Abiotic depletion (AD)	kg Sb_{eq}	0.291
Global warming (GW)	kg CO_{2eq}	350
Ozone layer depletion (OLD)	mg CFC-11_{eq}	92.8
Human toxicity (HT)	kg 1,4-DB_{eq}	426
Fresh water aquatic ecotoxicity (FE)	kg 1,4-DB_{eq}	28.2
Marine aquatic ecotoxicity (ME)	kg 1,4-DB_{eq}	$9.52 \cdot 10^4$
Terrestrial ecotoxicity (TE)	kg 1,4-DB_{eq}	0.493
Photochemical oxidation (PO)	kg C_2H_{2eq}	0.272
Acidification (AC)	kg SO_{2eq}	3.84
Eutrophication (EP)	kg$PO^{-3}_{4\ eq}$	0.686

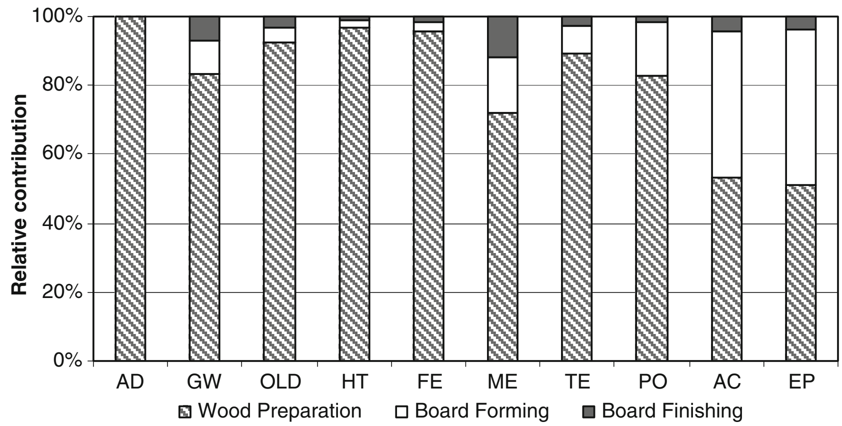
Global warming potential As shown in Fig. 2, the wood preparation subsystem was responsible for most of the GW. Chemical production (mainly phenolic resin) and electricity production were responsible for 33% and 39% of total carbon dioxide (CO_2) equivalent emissions, respectively (see Fig. 3). Fossil fuel consumption for electricity production (in all subsystems) accounted for more than 38% of the total contribution. However, it should be considered that the combustion of biomass (in this case, wood waste) in boilers to produce the thermal energy requirements gave rise to biogenic CO_2 emissions. This amount of CO_2 can be considered equal to that taken up by photosynthesis. Therefore, biomass burning is CO_2-neutral but not CO_2-free. Fossil CO_2 emissions gave the greatest contribution (98%) to this impact category, followed by N_2O (0.9%) and CH_4 (0.8%).

Ozone layer depletion potential Wood preparation subsystem was again the main contributor to OLD mainly due to the production of diesel required during chipping stage, which represents more than 70% of total contributing emissions. The second largest contributor to OLD was the electricity production (18%) and the remaining contributions were mainly related to the production of chemicals used and transport activities. Regarding emissions, Halon 1301 and 1211 represented 80% and 19% of total emissions (CFC-11 equivalent), respectively.

Human toxicity potential Approximately 97% of contributions to this impact category were associated with the wood preparation subsystem (see Fig. 2). Chemicals production represented more than 91%, mainly due to the phenolic resin (see Fig. 3). Substances contributing to HT potential were expressed as 1,4-dichlorobenzene equivalents. It is important to consider the waterborne emissions of benzene (60%) as well as airborne emissions of benzene (29%) and polycyclic aromatic hydrocarbons (3%).

Freshwater aquatic ecotoxicity potential A high percentage (96% of the total impact) of FE potential was linked to

Fig. 2 Relative contributions per subsystems (in %) to each impact category. Impact category acronyms: *AD* abiotic depletion, *GW* global warming, *OLD* ozone layer depletion, *HT* human toxicity, *FE* freshwater aquatic ecotoxicity, *ME* marine aquatic ecotoxicity, *TE* terrestrial ecotoxicity, *PO* photo-oxidant formation, *AC* acidification and *EP* eutrophication



wood preparation due to the contribution of chemical production (84%) and electricity production (8%). The balance was related to board forming (2.6%) and board finishing (1.4%), where 84% of the total impact arises from electricity production. Waterborne emissions, particularly those of phenol (50%), vanadium (20%) and formaldehyde (10%), dominated the contributions to this impact category.

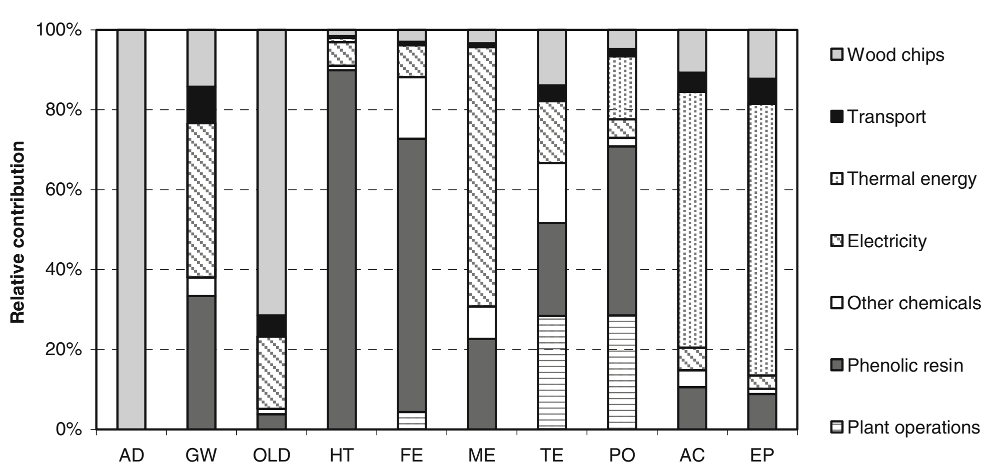
Marine aquatic ecotoxicity potential Electricity production was the main contributor to this category (>65%), followed by phenolic resin production (23%). Airborne emissions of hydrogen fluoride accounted for 80% of the total, followed by waterborne emissions of vanadium (6%) mainly from both processes.

Terrestrial ecotoxicity potential Operations which take place inside the plant represented more than 28% of total contributions to TE potential (see Fig. 3) mainly due to uncontrolled formaldehyde emissions, followed by phenolic resin production (23%). The main emissions contributing to this impact category were those of formaldehyde (31%) and vanadium (29%) from resin production and on-site machineries (dryer, presses and mat former) as well as mercury (22%) from electricity production.

Photochemical oxidants formation potential The wood preparation subsystem had the largest contribution to the potential impact of photochemical oxidant formation (83%). Again chemicals manufacture shown the highest contribution to this impact category (45%), followed by direct emissions derived from plant operations (such as drying and mat forming), which represented ~29%. Moreover, the on-site thermal energy production from biomass waste was another hot spot (~16%). The PO of the system studied was mainly caused by formaldehyde emissions from the drying and pressing steps (24% of total) as well as formaldehyde, cumene and propene emissions from phenolic resin manufacture (31%). The remaining emissions (especially those of SO_2) were closely related to energy use.

Acidification potential The wood preparation and board forming subsystems were the most important contributors

Fig. 3 Relative contributions per processes (in %) to each impact category. "Wood chips" includes not only the roundwood chipping step but also, all forest activities focused on roundwood production



to AC (53% and 43% respectively) followed by the board finishing subsystem according to Fig. 2. This result agrees with those of related studies (Rivela et al. 2006, 2007). Emissions of NO_x (64%) and SO_2 (33%) presented the greatest contributions to this impact category; they were mainly derived from the biomass boilers (overall thermal energy demand was satisfied in the plant using renewable resources), chemical production and fossil fuel combustion during green chips production and transportation (see Fig. 3). In fact, thermal energy production process represented 64% of total acidifying emissions.

Eutrophication potential Wood preparation subsystem had the largest contribution to this impact category (>51%) followed by board forming and board finishing (see Fig. 2). This result was associated with the high diesel consumption by chipping machine as well as energy consumption in the pressing step. Thermal energy plant was the main contributor to this impact category (68% of total) according to Fig. 3. Airborne NO_x emissions showed the greatest contribution to EP (93%), followed by those of COD (5%) to water. NO_X emissions originating from the biomass energy converters were responsible for 21% of the total eutrophying emissions. Other processes involving eutrophying emissions were phenolic resin and green chips production (mainly due to combustion emissions and diffuse emissions from fertilisers application) as well as transport activities (see Fig. 3).

4 Discussion

LCA allows location of areas in a process chain which need improvements. In this study, the hardboard production process was analysed in detail with the aim of identifying the environmental burdens and hot spots of one of the most important composite materials used. According to Fig. 3, four processes significantly influenced the environmental impacts of the production system: electricity and phenolic resin production, residual wood burning (thermal energy production) and wood chipping stage. These results are in agreement with other reports (Nebel et al. 2006; Rivela et al. 2006, 2007; Werner and Richter 2007).

The hardboard plant investigated was an important consumer of renewable energy since all heat requirements (steam for defibrator, hot oil for pressing and hot gas for drying) were satisfied by on-site residual biomass burning. Approximately 98% of the energy consumed came from internal recycling (rejected hardboard, sanding dust, sawdust, trimmings etc.) and only 2% from external biomass (wood waste from other factories and forest operations). The biomass boilers showed a high contribution to AC and EP due to NO_x and SO_2 emissions (Jawjit et al. 2007).

Chemicals production had a considerable contribution (~40%) to GW, TE and PO. Its contribution to impact categories related to toxicity such as HT and FE was really high (more than 84% of total). Wood composite materials are commonly produced by blending or spraying lignocellulosic materials with a synthetic binder such as phenol- or urea-formaldehyde resin or isocyanate, which contribute to the emission of toxicity pollutants.

Abiotic resource depletion concerns both non-renewable and renewable resources. In this study, however, only the depletion of non-renewable resources (minerals and fossil fuels) was taken into account. Wood chipping stage was the main contributor to AD due to high diesel consumption in the corresponding machinery.

With regard to GW, a detailed analysis was carried out to identify the processes with the highest contributions. In particular, the wood preparation subsystem contributed on average 84% of the CO_2-equivalent emissions, while the contribution of the remaining subsystems amounted to ~16%. According to Fig. 4, improvements focussing on chemicals production could be made in order to cut not only the emissions of CO_2- but also CFC-11- and 1,4-dichlorobenzene-equivalent derived from wood preparation subsystem. Moreover, electricity production showed high contribution to the CO_2-equivalent emissions in all subsystems under study and a sensitivity analysis could be desirable to assess its influence on the environmental results.

The drying of resinated fibres and mat forming were two of the most important unit processes from an environmental point of view since they were important sources of formaldehyde emissions (see Table 1). These processes together contributed on average 31% of the PO. Formaldehyde is a fairly reactive compound with many negative effects on health and environment. A remarkable improvement for the process in this regard could be achieved if formaldehyde-free (preferably binderless) bonding methods were used. Some authors are working in this area and good results have been obtained by activating wood fibres with Fenton's reagent (H_2O_2 + Fe^{2+}; Widsten et al. 2003a, b) or phenol-oxidising enzymes (Widsten and Kandelbauer 2008) (laccase and peroxidase) to produce binderless fibreboard. Another improvement alternative is the utilisation of binders from renewable feedstocks (e.g. soy-based binders). Environmental concerns have caused a resurgence of interest in developing new products for the composites industry to replace formaldehyde-based binders. In fact, they have recently been commercially utilised for the manufacture of common wood products such as plywood, oriented strandboard, particleboard and MDF (United Soybean 2007).

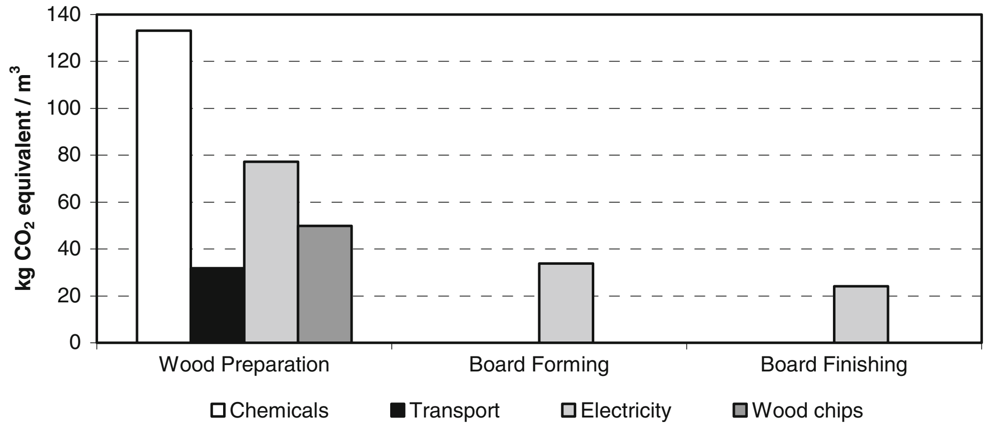


Fig. 4 Distribution of total carbon dioxide (CO_2) equivalent emissions per subsystem (wood preparation, board forming and board finishing) and origin (chemicals production, transportation and electricity production)

4.1 Sensitivity analysis of electricity generation profile

According to literature, the hardboard manufacturing process at the plant studied can be considered representative of the state-of-art (US EPA 2002) and common to processes carried out in other European countries. However, factors with a strong geographical dependence such as the electricity profile generation considerably affect the results. Electricity can be produced with technologies with quite diverse environmental properties. Analysing marginal technologies (that is, technologies actually affected by a small change in demand) can be proposed in comparative life cycle assessments in order to show the best reflection of the actual consequences of a decision (Weidema et al. 1999; Ekvall and Weidema 2004), specifically in electricity production scenarios. However, the dependence on the electricity generation profile was analysed in this study considering six European scenarios (Table 4), where different sources of electricity were included: oil, coal, gas, nuclear and hydroelectric. These six scenarios are representative of electricity generation profiles in Europe and all inventory data for electricity generation profiles come from the Dones et al. (2007). This assessment was assumed in order to identify how the environmental profile of the hardboard manufacture can change depending on the location of the mill.

Figure 5 shows the results from the characterisation phase of the LCI assessment. The values were indexed using hardboard-A as the baseline (index=100 for each impact category). According to the results, the alternative scenarios hardboard-C and hardboard-F considerably reduced the contributions to some impact categories (GW, OLD, HT, ME, PO and EP). Hardboard-B, hardboard-D and hardboard-E got to reduce the contributions only to OLD.

Scenarios with high electricity consumption from non-renewable sources (hardboard-B, hardboard-D and hardboard-E) showed higher contributions to ecotoxicity and hydrocarbon emissions due to incomplete combustion of fossil fuels (Fig. 5). In addition, these scenarios showed the highest contribution to GW, AC and EP (see Fig. 5) due to a lower contribution of hydroelectric energy as compared to hardboard-A (see Table 4). Specifically, the SO_2 and NO_x emissions for hardboard-B and hardboard-D were twice as large as with hardboard-A mainly due to the electricity profile. According to Fig. 5, the largest environmental reductions (up to 31%) were obtained for GW, OLD and ME. All electricity generation technologies generate CO_2, other greenhouse gases and OLD substances. Fossil fuel technologies (coal, oil and gas) have the largest CO_2-equivalent emissions. By contrast, renewable (e.g., hydroelectric, biomass, wind, solar and marine technologies) and nuclear energy systems are known as low-carbon or carbon-neutral. However, all electricity generation systems emit CO_2 at some point during their life cycle (raw material extraction, construction and maintenance). From an environmental point of view, scenarios hardboard-C and hardboard-F were more favourable because of their reliance on nuclear and hydroelectric power, respectively, instead of fossil fuels.

The variability in the results allows identification of an important point in the environmental profile of hardboard plants: the strong dependence on geographical parameters such as electricity generation profile.

5 Conclusions

This work focussed on the identification and characterisation of wet-process fiberboard (hardboard). An Austrian hardboard plant considered representative of the state-of-art was selected to study the process in detail. The hot spots over the life cycle of the hardboard manufacturing process (cradle-to-gate perspective) were identified from the inventory analysis and impact assessment results. Chemicals and electricity production considerably influenced the environ-

Table 4 Distribution (in %) of electricity sources for each scenario considered under study

Electricity source	Scenarios					
	Hardboard-A Austria	Hardboard-B Spain	Hardboard-C France	Hardboard-D Germany	Hardboard-E Central Europe[a]	Hardboard-F Nordic countries[b]
Oil	1.6	4.8	1.4	1.1	2.4	1.8
Coal	9.9	37.0	4.9	50.6	71.2	7.8
Gas	8.7	8.7	2.7	11.0	5.9	4.9
Hydroelectric	79.7	16.0	13.8	4.8	4.2	60.5
Nuclear	0.0	30.5	76.6	30.4	15.6	19.9
Others	0.1	3.0	0.6	2.1	0.7	5.2

[a] Czech Republic, Hungary, Poland and Slovak Republic

[b] Denmark, Finland, Norway and Sweden

mental impacts. These processes were significant sources of atmospheric and waterborne emissions. Production of the main raw material (green chips) was identified as important contributor to some impact categories such as abiotic depletion due to the high diesel consumption by chipping machines. On the contrary, forest activities related to roundwood production showed a negligible contribution in all impact categories. Fibre drying and mat forming (internal plant activities) were two of the most relevant contributing processes in terms of photochemical oxidant formation and terrestrial ecotoxicity due to uncontrolled formaldehyde emissions, while biomass burning played an important role in both acidification and eutrophication (mainly due to NO_x emissions). In addition, the results of the sensitivity analysis showed a considerable dependence on the electricity generation profile; renewable and nuclear energy systems seem to be the best option.

6 Recommendations and perspectives

The results obtained provide valuable information that can assist wood panel plants to improve their environmental performance and sustainability. Our research continues to assess the use phase and final disposal of panels to complete the LCA study. Future work will focus on identifying the environmental burdens associated with another important type of wood panel, plywood, which is commonly used for both interior and exterior applications (walls, floors, ceiling panels, containers, boxes and packaging).

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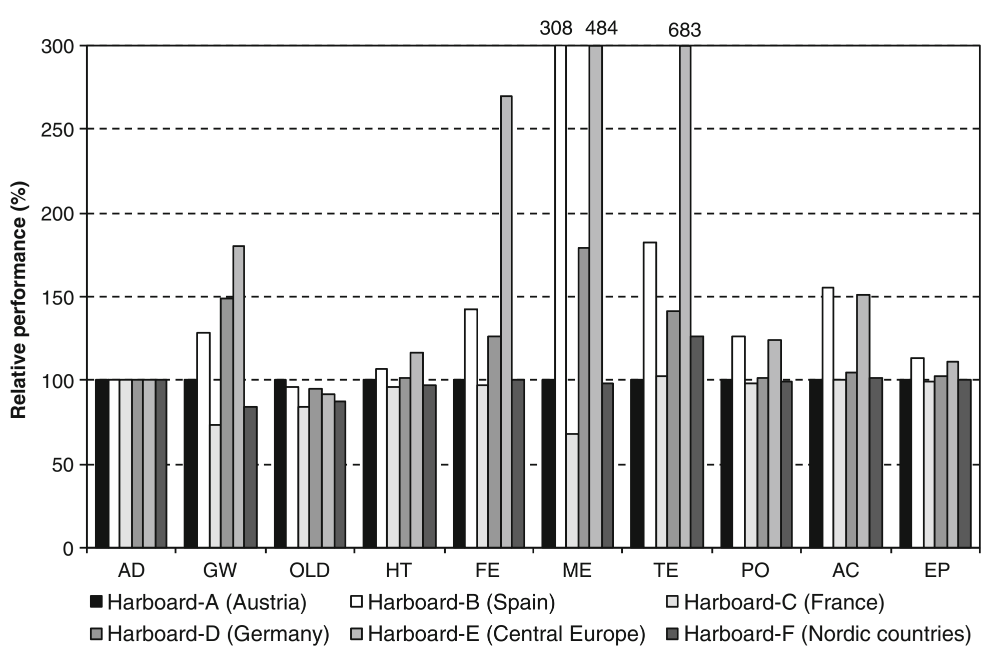

Fig. 5 Relative environmental profile of the different alternative scenarios, the current generation profile in Austria (hardboard-A) serving as the baseline (Index=100)

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